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SIXTH INTERIM TOPICAL REPORT

on

A STUDY OF THE MECHANICS
OF CLOSED-DIE FORGING

IMPORTANT FACTORS IN SELECTION AND
USE OF EQUIPMENT FOR FORGING

to

ARMY MATERIAL AND
MECHANICS RESEARCH CENTER

November 15, 1969

by

T. Altan, H. J. Henning, and A. M. Sabroff

Contract DAAG46-68-C-0111

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FOREWORD

This topical report, "Important Factors in Selection and Use of Equipment for Forging" covers the review work performed under Contract No. DAAG46-48-C-0111 with Battelle Memorial Institute of Columbus, Ohio, from August 30, 1969, to October 30, 1969.

This work was administered under the technical direction of Mr. Dennis Green of the Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172.

This program was carried out under the supervision of Mr. A. M. Sabroff, Chief of the Metalworking Division, and Mr. H. J. Henning, Associate Chief of the Metalworking Division. Dr. T. Altan, Senior Scientist, is the principal investigator.

TABLE OF CONTENTS

IMPORTANT FACTORS IN SELECTION AND USE OF EQUIPMENT FOR FORGING

by

T. Altan, H. J. Henning, and A. M. Sabroff

ABSTRACT

The increasing degree of sophistication observed in the forging industry requires a sound and fundamental understanding of equipment capabilities and characteristics. The equipment behavior influences the forging process since it determines the feasibility of forging a part and it affects the rate of deformation and the temperature conditions. The load and energy requirements of a given forming process must be compatible with the load, energy, time and accuracy characteristics of a given forging machine.

Discussed in this report are the important and basic characteristics of hydraulic presses, mechanical-crank- or eccentric-type presses, screw presses and hammers. The equipment behavior is considered in relation with the forging process. Most of the background used in this report was obtained from foreign sources since there appears to be very little information available in the U. S. literature on this subject.

INTRODUCTION

Recent developments in the forging industry indicate strong emphasis on: (a) increasing the production rate, (b) increasing the precision in forging (by better designing the process), and (c) expanding the capacity to forge larger and more intricate parts from more difficult-to-forge materials.

Improvement of the forging process is very closely related to a better understanding and use of equipment capabilities. The establishment of characteristic data for various types of forging equipment would be very useful for both the user and the manufacturer and would be helpful in increasing efficiency in the forging industry.[(1)*] Increased knowledge on equipment would specifically contribute to:

(1) More efficient and economical use of existing equipment

(2) More exact definition of the maximum plant capacity

(3) Better communication between the equipment user and the equipment builder and a more efficient way of ordering new equipment

(4) Development of more refined processes such as precision forging of gears, and of turbine and compressor blades in cooperation with the equipment builder

*References are listed on page 30.

(5) Development of techniques for forging high-strength materials such as titanium- and nickel-based alloys with increased precision

(6) Establishment of interchangeability between different types of equipment to better meet delivery and scheduling conditions.

Various types of forging equipment and their characteristics can not be adequately discussed without the simultaneous consideration of (a) the mechanical behavior of the material to be forged and (b) the specific load and energy requirements of the forging process to be carried out. Consequently, a short review of these two factors is necessary.

MECHANICAL BEHAVIOR OF METALS UNDER PLASTIC DEFORMATION

The flow behavior of a metal during deformation is influenced by:

(a) Factors unrelated to the deformation process such as chemical composition, metallurgical structure, phases, grain size, segregation, prior strain history

(b) Factors explicitly related to the deformation process:

(1) Temperature of deformation (θ),

(2) Degree of deformation or strain ($\bar{\epsilon}$),

(3) Rate of deformation or strain rate ($\dot{\bar{\epsilon}}$).

Thus, the flow stress ($\bar{\sigma}$) which determines the resistance of a metal to deformation, is expressed as follows:

$$\bar{\sigma} = F\ (\theta, \bar{\epsilon}, \dot{\bar{\epsilon}}) \quad . \tag{1}$$

Equation (1) illustrates that the flow stress ($\bar{\sigma}$) is a function of temperature (θ), strain ($\bar{\epsilon}$), and strain rate ($\dot{\bar{\epsilon}}$).

In hot forging of metals at temperatures above the recrystallization temperature, the influence of strain upon flow stress is insignificant while the influence of strain rate (i.e., rate of deformation) becomes increasingly important. Inversely, at room temperature (i.e., in cold forming) the effect of strain rate upon flow stress is negligible while the effect of strain upon flow stress (i.e., strain hardening) is most important. Consequently, in hot forging of most metals at temperatures above the recrystallization temperature, Equation (1) can be reduced to:

$$\bar{\sigma} = F\ (\theta, \dot{\bar{\epsilon}}) \quad . \tag{2}$$

Equation (2) states that at high temperatures the flow stress ($\bar{\sigma}$) is only influenced by deformation temperature (θ) and by the deformation rate, i.e., strain rate ($\dot{\bar{\epsilon}}$).

While it is well known that the flow stress of a metal decreases with increasing temperature and increases with increasing strain rate, the degree of dependency of the flow stress upon the temperature and strain rate, although extremely important, is largely ignored. Figure 1 illustrates that a large variation in strain rate has a small effect upon the flow stress of 4340 steel and 1100 aluminum while its effect upon the titanium alloy, Ti-13V-11Cr-3Al is considerable.[2] Figure 2 shows the effects of relatively small temperature changes on the flow stress of different materials.[2] It is evident that the titanium alloy would require considerably higher forging loads for a relatively small drop in forging temperature.

The above discussion explains why changes in temperature during hot forging (due to die chilling, excessive cooling in handling, or internal heat generation because of deformation) and in strain rate (due to velocity-displacement characteristic of the equipment used) can have drastically different consequences for different materials.

LOAD AND ENERGY REQUIREMENTS OF A FORMING PROCESS

For a given material a specific forming process such as closed-die forging, forward and backward extrusion, bending, etc., requires a specific amount of energy. This fact is illustrated in Figure 3 where load-versus-displacement curves are given for various forming operations with steel. The surface area under the load-displacement curve is the deformation energy necessary to carry out that specific deformation process. Figure 4 shows the load build-up and release times in hot upsetting of steel under different forging machines.[3]

The curves given in Figures 3 and 4 illustrate qualitatively the variation of the forming load during a specific process and the deformation energy required to carry out a given process. The absolute load values will vary with the flow stress of the material as well as with the friction conditions. The effect of strain rate and temperature in upsetting is well shown by the shape of the curves given in Figure 4 where, for the same process, material and initial billet temperature, different forging loads and energies have been required by different machines.

It is interesting to note at this point that the German-Machine-Tool Builders Association sponsored at the Technical University of Stuttgart a research project to develop a hydraulic simulator which simulates the load-versus-displacement curves of various forming processes. The slide displacement of a hydraulic or mechanical press is measured with magnetic sensors. A very high speed hydraulic system and a small computer that programs the pressure sequence simulate the forming process in a hydraulic cylinder placed on the press bed while the press is operated. Thus, the press can be operated under simulated production conditions for measurements of stresses and deflections in the press frame and for measurement of the ram velocity and flywheel slowdown.

Thus, in hot forging, not only the material and the forged shape, but also the rate of deformation and die chilling effects, and, therefore, the type of equipment used, determines the forging load and energy required for the process. This fact is not always

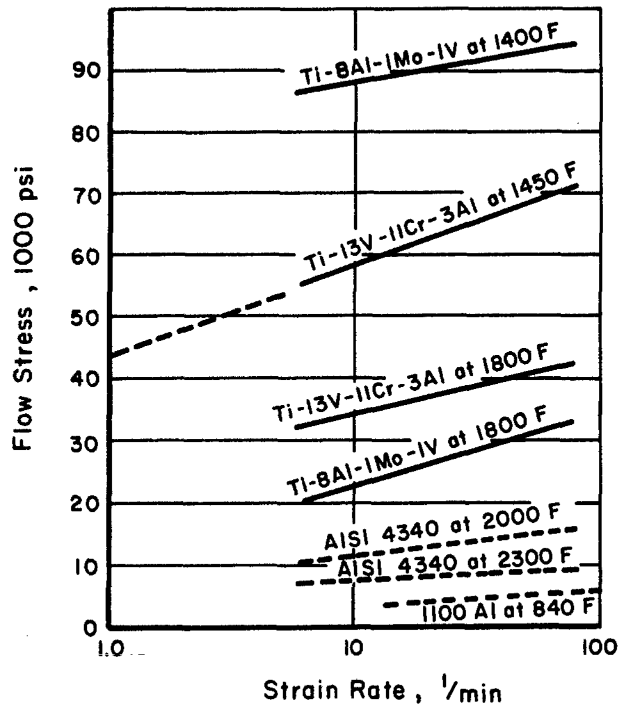


FIGURE 1. EFFECT OF STRAIN RATE ON FLOW STRESS FOR SEVERAL ALLOYS AT VARIOUS FORGING TEMPERATURES (2)

Flow stresses determined at 10 percent upset reduction.

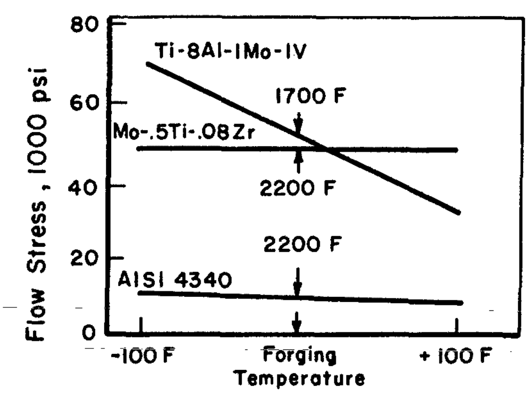


FIGURE 2. INFLUENCE OF TEMPERATURE CHANGES ON THE FORGING PRESSURES OF THREE ALLOYS AT THEIR RESPECTIVE FORGING TEMPERATURES(2)

Flow stresses determined for 10 percent upset reduction.

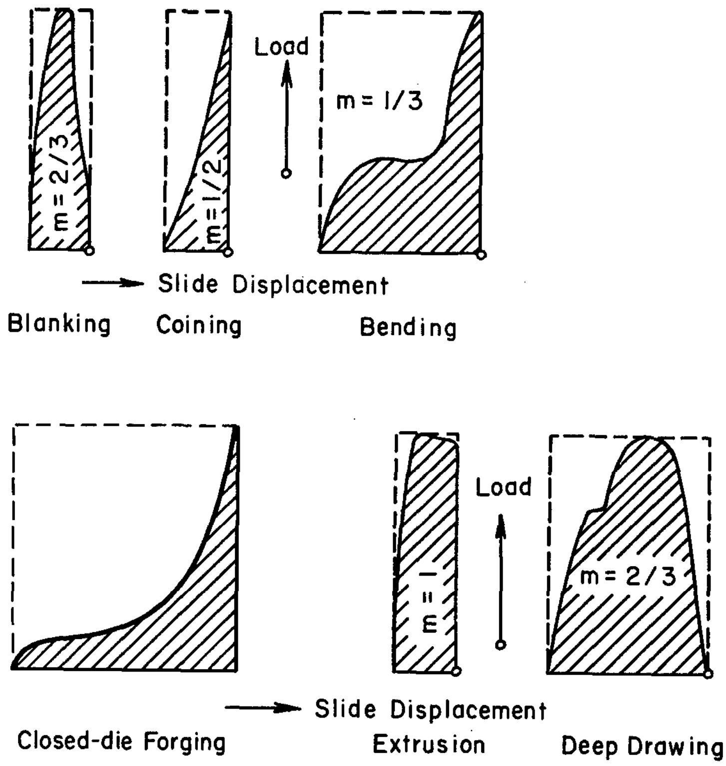


FIGURE 3. LOAD VERSUS DISPLACEMENT CURVES FOR VARIOUS FORMING PROCESSES(3)

Deformation energy = load displacement· m.

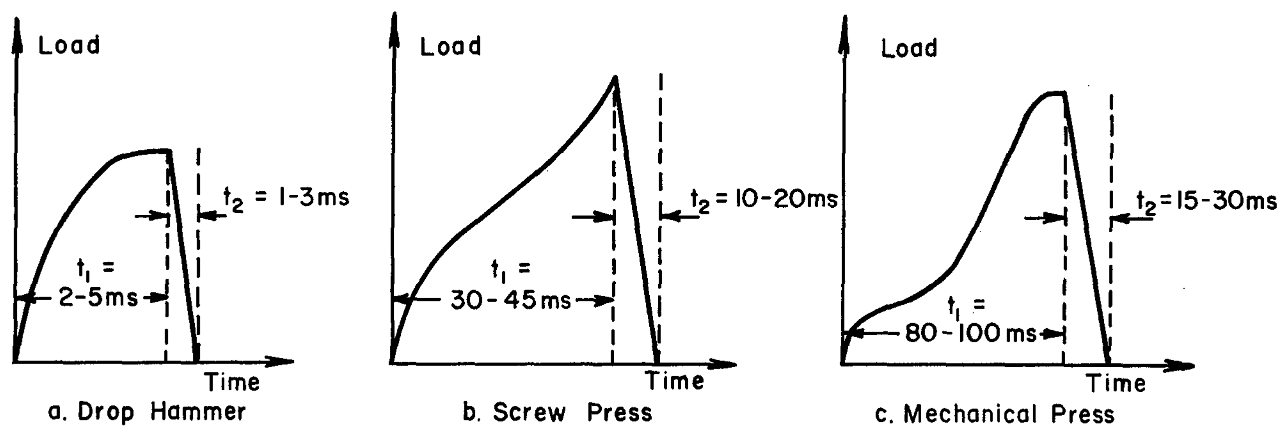


FIGURE 4. LOAD VERSUS TIME CURVES FOR DIFFERENT TYPES OF EQUIPMENT IN HOT UPSETTING OF THE SAME SIZE STEEL SAMPLE(3)

t_1 = pressure build-up time in milliseconds
t_2 = pressure release time in milliseconds.

clearly acknowledged although it is of paramount importance in understanding the relationship between process and equipment.

CHARACTERISTIC DATA ON FORGING EQUIPMENT

Characteristic data of a machine is defined here as all data about that machine which are pertinent to its economical use. These data are necessary for optimum selection of a type of equipment for a given process. For further discussion it is useful to classify various forging machines according to their characteristics. This classification, originally suggested by Professor Kienzle, is given in Table 1.[4, 5] The data listed in Table 1 are described below by using the subscript "M" to designate the forging machine and the subscript "P" to designate the process.

Characteristic Data for Load and Energy

Available Energy (E_M) (in ft-lb or kgm) is the energy supplied by the machine to carry out the deformation during an entire stroke. Available Energy (E_M) does not include either (E_f), the energy necessary to overcome the friction in the bearings and slides, or (E_d), the energy lost because of elastic deflections in the frame and in driving system.

Available Load (L_M) (in tons) is the load available at the slide to carry out the deformation process. This load might be constant as in hydraulic presses or it might vary with the slide position in respect to "bottom dead center" (BDC) as in mechanical presses.

Efficiency Factor (η) is determined by dividing the energy available for deformation (E_M) by the total energy (E_T) supplied to the machine, i.e.,

$$M = \frac{E_M}{E_T} \quad . \tag{3}$$

The total energy (E_T) also includes in general: (a) the losses in the electric motor (E_e), (b) the friction losses in the gibs and in the driving system (E_f), and (c) the losses due to total elastic deflection of the machine (E_d). Consequently,

$$E_T = E_e + E_f + E_d + E_M \tag{4a}$$

or

$$\eta = \frac{E_M}{E_e + E_f + E_d + E_M} \quad . \tag{4b}$$

TABLE 1. IMPORTANT CHARACTERISTIC DATA FOR MACHINE TOOLS FOR FORGING[4, 5]

	Static Acting		Dynamic Acting				
	Hydraulic Presses		Hammers				Crank Presses
	Direct Driven	Accumulator Driven	Drop	Pneumatic Hydraulic	Counterblow	Screw Presses	Horizontal Upsetter
Machined Restricted by:	Load	Load and Energy	Energy	Energy	Energy	Energy	Displacement
Characteristic data for load and energy							
Available energy (E_M), ft-lb or kgm		x	x	x	x	x	x
Available load (L_M) t	x	x				x	x
Efficiency (η)			x	x	x	x	
Stiffness (C), see below							
Time-Dependent Characteristic Data							
Strokes per minute (n), -/min	x	x	x	x	x	x	x
Contact time under pressure (t_p), sec	x	x				x	x
Velocity under pressure (V_p), in./sec	x	x	x		x	x	x
Characteristic Data for Accuracy							
Of the unloaded machine							
Stationary surfaces and their relative positions	x	x	x	x	x	x	x
Of the loaded machine (on center and off center loading)							
Dynamic tilting of the ram			x		x	x	x
Ram and frame deflections	x	x				x	x
Stiffness C	x	x				x	x

The following conditions must be satisfied during a forming process:[6]

$$L_M \geq L_p \text{ at any time during forming} \tag{5}$$

or

$$E_M \geq E_p \text{ during an entire forming cycle .} \tag{6}$$

Equation (5) states that the load available from the machine (L_M) must be at any stroke position larger than or equal to the load required by the forming process. If this condition is not full-filled in a hydraulic press, the press will stall without accomplishing the required deformation. In a mechanical press the friction clutch might slip or, if no safety devices for overloading are provided, the press might be overloaded and the tooling or the press itself might be damaged.

Equation (6) states that the available energy (E_M) during a stroke must be larger than the energy required by the process. If this condition is not satisfied, the flywheel will slow down to unacceptable speeds in a mechanical press, and, in a screw press or hammer, the part will not be forged completely in one blow.

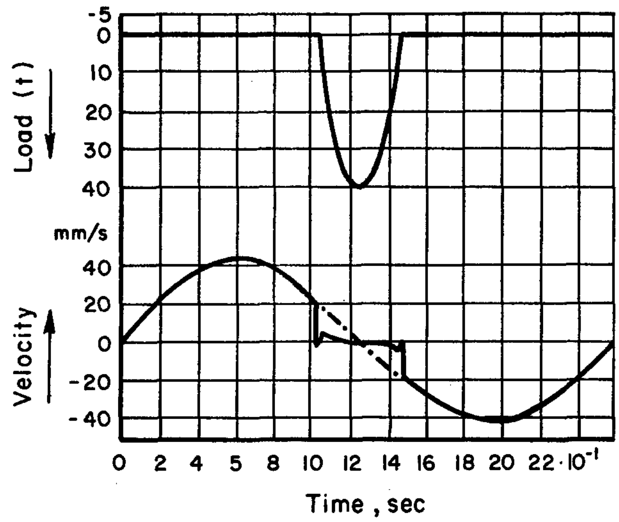
Time-Dependent Characteristic Data

Number of Strokes per minute (n) is one of the most important characteristics of any machine since it determines the production rate. In hydraulic presses, for instance, the number of strokes per minute can only be defined for a given forging stroke. In continuously operated mechanical presses, after each stroke the electric motor must bring the flywheel back to its idle speed before the next stroke starts. Consequently, in a mechanical press, the number of strokes per minute will be influenced by the amount of energy consumed during one stroke, i.e., by the magnitude of flywheel slowdown. If, however, the press is operated intermittently because the part must be removed and new stock placed in the die, then the number of strokes per minute is not determined by the press, but by handling and loading techniques.

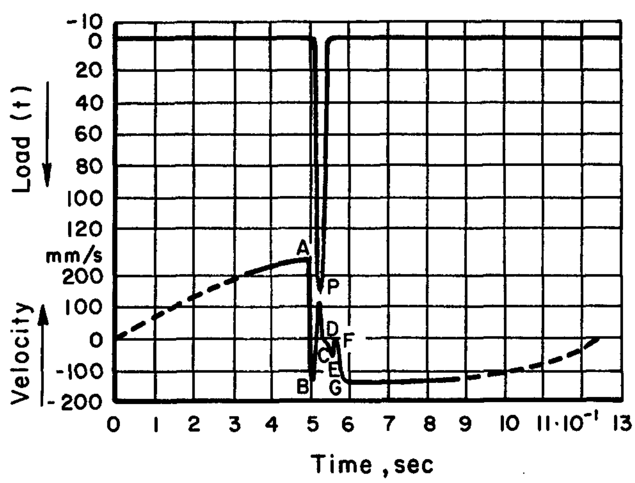
Contact time under pressure (t_p) is the time during which the forging remains in the die under deformation load. The heat transfer between the hotter forged part and the cooler dies is most significant under pressure. Beck's work on workpiece and die temperatures in closed-die forging clearly showed that the heat-transfer coefficient is about 17 times larger under forging pressure than under free contact conditions.[7] Consequently, the contact time under pressure greatly influences wear, wash out, and permanent set in forging dies. In addition, cooling of the workpiece and the associated increase in flow stress are also related to the contact time.

Velocity under pressure (V_p) is the velocity of the slide under load. This is an important variable because it determines (a) the contact time under pressure and (b) the rate of deformation or the strain rate. The strain rate influences the flow stress of the forged material and consequently affects the load and energy required for forging.

The velocity under pressure (V_p) must be distinguished from the nominal velocity of the slide without load. This fact is illustrated in Figure 5 for a coining operation.[8]



a. Coining in Crankpress at 23.6-Rpm Crank Speed



b. Coining in Screw Press

FIGURE 5. VELOCITY UNDER PRESSURE (V_p) VERSUS TIME CURVES IN COINING UNDER A CRANK PRESS AND UNDER A SCREW PRESS(8)

--- real velocity
— theoretical velocity.

In a mechanical press, Figure 5a, upon contact between the slide and the workpiece, the clearance in the bearings disappears and the slide slows down considerably. While the forming load increases, the pitman arm, the driving system, and the press frame deflect elastically thus causing a deviation from the ideal velocity-versus-time curve. In the example shown in Figure 5a, the actual velocity is only one-fourth of the ideal velocity.

In a screw press, which is generally a faster forging machine than a mechanical press, upon contact with the workpiece, the clearances in the screw threads cause the slide velocity to drop to zero and even become negative for a very short time. In the example seen in Figure 5b, the actual slide velocity reaches two-fifths of the ideal velocity.

In most direct-driven hydraulic presses, upon contact with the workpiece, the ram dwells for a short time until the pump has built up enough pressure in the cylinder to push the ram downward. Thus, after a dwell, the ram accelerates to the nominal constant press speed. The duration of dwell depends upon the pumping capacity of the hydraulic system and upon the compressibility of the pressure medium.

Hydraulic presses are usually slower than hammers, mechanical presses, and screw presses. The ram velocities for hydraulic presses under load are usually in the range of 5 to 15 in./sec, compared with mechanical presses at 5 to 30 in./sec, hammers at 160 to 240 in./sec and screw presses at 20 to 50 in./sec.

Characteristic Data for Accuracy

Unloaded machine – the stationary surfaces and their relative positions are established by:

(a) Clearances in the gibs

(b) Parallelism of upper and lower beds

(c) Flatness of upper and lower beds

(d) Perpendicularity of the slide motion with respect to the lower bed

(e) Concentricity of tool holders.

In backward extrusion of thin-walled cups for instance, a slight unparallelism of the beds or a slight deviation of the slide motion from ideal perpendicularity would result in excessive bending stresses on the punch and in nonuniform wall and bottom thickness in the extruded cups.

Loaded machine – the tilting of the ram and the ram and frame deflections, particularly under off-center loading, might result in excessive wear of the gibs, in thickness deviations in the forged part, and in excessive tool wear. In multiple-operation processes, the tilting and deflections across the ram might determine the feasibility or the economics of forging a given part. These considerations are generally well known and are valid for single- as well as multiple-point slide presses.

The stiffness (C) of a press, which usually receives less attention, is the ratio of the load (L_M) to the total deflection between the upper and lower beds of a press, i.e.,

$$\text{Stiffness (C) in tons}/\mu\text{in.} = \text{Load } L_M/d \quad . \qquad (7)$$

The total elastic deflection (d) includes the deflection of the slide and the pitman arm (~20 to 30 percent of the total), the deflection of the frame (~25 to 35 percent of the total), and the deflection of the driving system (~30 to 40 percent of the total). The main influences of the stiffness (C) upon the forging process can be summarized as follows:[8]

(1) Under identical forging load (L_M) the deflection energy (E_d) is smaller for a stiffer press (larger C). The deflection energy is given by

$$E_d = \frac{1}{2} d\, L_M \quad , \qquad (8a)$$

and with Equation (7),

$$E_d = \frac{L_M^2}{2\,C} \quad . \qquad (8b)$$

Equation (8b) indicates that for a given load (L_M), the deflection energy (E_d) is larger for a smaller stiffness (C). The deflection energy is the potential elastic energy stored in the press during the load build-up. During unloading this energy is lost in most closed-die forging operations; consequently, the overall efficiency of a forging machine (n) decreases with decreasing stiffness (C) as already discussed in Equations 4a and 4b.

(2) The higher the stiffness, the lower the deflection of the press. Consequently, the variations in the forging thickness, due to volume or temperature changes in the stock, are also smaller. In open back inclinable (OBI) type presses, lower deflections contribute to longer tool life.

(3) The stiffness influences the velocity-versus-time curve under load. Since a less stiff machine takes more time to build up and remove pressure, the contact time under pressure (t_p) is longer. This fact contributes to the reduction of tool life in hot forging.

It should be pointed out, however, that increased stiffness means increased cost of the machine. Therefore, stiffness should not be overemphasized and required in operations where the elastic deflections are not necessarily critical. Most forging presses behave quasistatically; therefore, the stiffness of a press can be determined under static loading. In very high velocity operations, however, the vibrations in the press frame, in the driving mechanism of mechanical presses, and in the hydraulic system of hydraulic presses, might become important. Very little information is found in the literature on this subject.[3]

CHARACTERISTICS OF DIFFERENT TYPES OF EQUIPMENT FOR FORGING

After the general discussion of the characteristic data for various forging machines, it is useful to review the outstanding features of each type of equipment and its principle of operation.

Hydraulic Presses

Hydraulic presses are well known and widely used in all areas of metalworking. At the present state of development they are efficient and economical and their reliability compares favorably with that of mechanical presses.[9, 10] Hydraulic presses are essentially load-restricted machines, i.e., their capability for carrying out a forming operation is limited mainly by the maximum available load. The following outstanding features are offered by hydraulic presses:

(1) In direct-driven hydraulic presses, the maximum press load is available at any point during the entire ram stroke. In accumulator-driven presses, the available load decreases slightly depending upon the length of the stroke and upon the load-displacement characteristics of the forming process.

(2) Since the maximum load is available during the entire stroke, relatively large energies are available for deformation. This is why the hydraulic press is ideally suited for processes such as tube or bar extrusion requiring a nearly constant load over a long stroke.

(3) Within the capacity of a hydraulic press, the maximum load can be limited in order to protect the tooling. In this case, it is not possible to exceed the set load since the pressure-release valve limits the fluid pressure acting upon the ram.

(4) Within the limits of the machine, the ram speed can be varied continuously at will during an entire stroke cycle. Adequate control systems can regulate the ram speed with respect to forging pressure or product temperature. This control feature can offer a considerable advantage in optimizing forming processes. An excellent example is the isothermal extrusion of light alloys in which constant product temperature is maintained by slowing down the ram speed as extrusion progresses.

Load capacities for hydraulic presses range from a few tons to many thousands of tons. The two largest presses in the United States are rated at 50,000 tons, while the largest Soviet press is rated at 75,000 metric tons. The hydraulic presses are, in general, slower than hammers, mechanical presses, and screw presses. Consequently, the contact times under load are relatively larger which contributes to cooling of the forged part and wear of the dies.

Two types of hydraulic-press drives give different time-dependent characteristic data of the presses:[11, 12, 13]

(1) Direct-driven presses usually have hydraulic oil as a working medium. A sequence of operations in such a vertical press is as follows. The upper ram falls under gravity and oil is drawn from the reservoir into the ram cylinder through the suction of this free fall. (In horizontal presses the ram is moved with low pressure.) Upon contact with the workpiece, the valve between the ram cylinder and the reservoir is closed and the pump builds up pressure in the ram cylinder. When the upper ram reaches a predetermined position, or when the pressure reaches a certain value, the pressure is released and diverted to lift the ram.

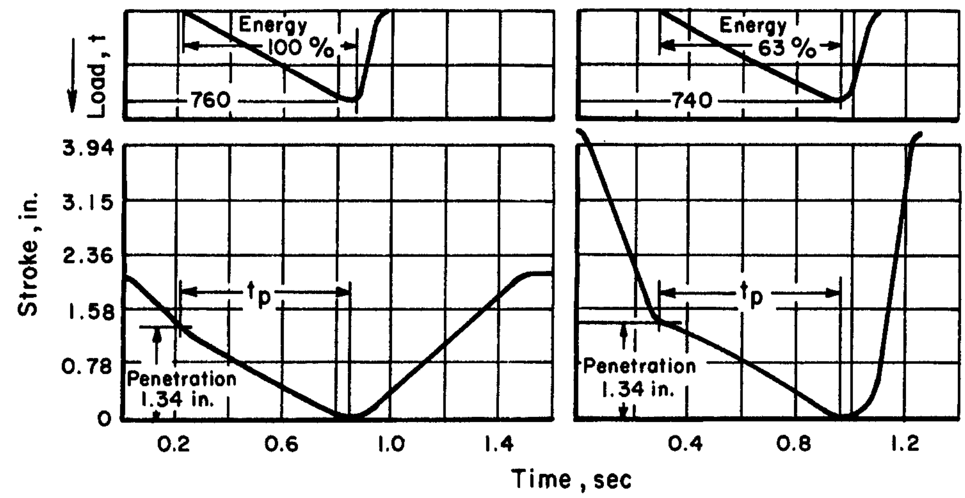
(2) Accumulator-driven presses usually have a water-oil emulsion as a working medium, and use nitrogen or air-loaded accumulators to keep the medium under pressure. The sequence of operations is essentially similar to the direct-driven press except that the pressure is built up by means of the pressurized water-oil emulsion in the accumulators. Consequently, the rate of penetration, i.e., the ram speed under load, is not directly dependent upon the pump characteristics and can vary depending upon the pressure in the accumulator, upon the compressibility of the pressure medium, and the resistance of the workpiece to deformation. Toward the end of the stroke, the available load at the ram decreases because the working medium expands as deformation progresses.

Figure 6 shows the load-versus-time and the displacement-versus-time curves for two types of hydraulic-drive systems in cogging (large penetrations). The corresponding information is given in Figure 7 for planishing (small penetrations). Data on both drive systems are given below:[12]

	Accumulator-Driven, Water-Oil Emulsion	Direct-Driven, Oil
Max. Load, ton	900	900
Motor HP	610	610
Effective Pump HP	500	1000[a]
Pumped Volume, g/min	291	336
Pump Pressure, psi	2850	5000

(a) Overloading is possible.

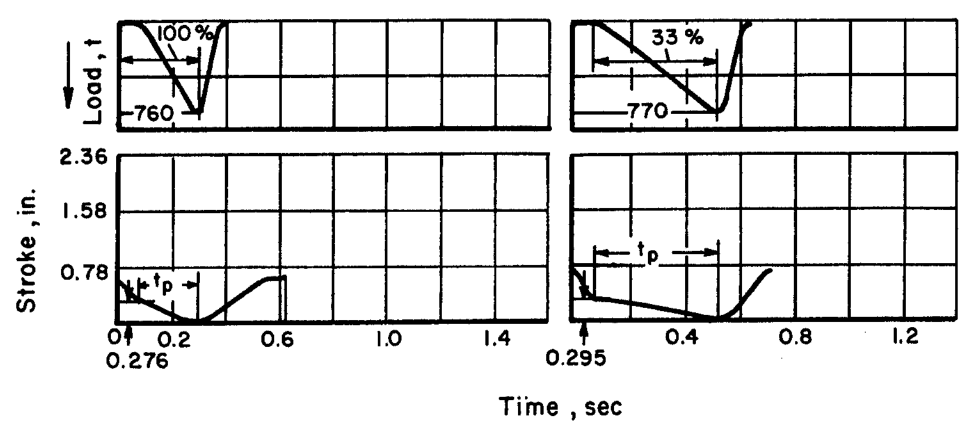
In Figure 6 it is seen that at 85 percent of the press capacity, for a penetration of 1.34 inches the contact times under pressure (t_p) are approximately the same for both drive systems (0.63 sec and 0.67 sec). The energy delivered by the direct-driven press is only 63 percent of the energy delivered by the accumulator-driven press for the same cogging operation. The direct-drive system gives also a higher number of strokes per minute (48 versus 37). This is, however, due to rapid return of the ram as seen in Figure 6b.



a. Accumulator drive
n = 37 strokes/min
t_p = 0.63 sec
v_p = 2.1 in./sec

b. Direct drive
n = 48 strokes/min
t_p = 0.67 sec
v_p = 2.12 in./sec

FIGURE 6. COMPARISON OF TWO 900-t FORGING PRESSES IN COGGING[12]



a. Accumulator Drive
n = 96 strokes/min
t_p = 0.21 sec
v_p = 1.3 in./sec

b. Direct Drive
n = 83 strokes/min
t_p = 0.45 sec
v_p = 0.67 in./sec

FIGURE 7. COMPARISON OF TWO 900-t FORGING PRESSES IN PLANISHING[12]

Figure 7 illustrates the data obtained for these two presses for planishing operation at 85 percent of the press capacity. For 0.276-inch penetration, the accumulator-driven press gives considerably shorter contact times (0.21 sec versus 0.45 sec) although the number of strokes per minute is in the same range for both presses.[12]

The examples illustrated in Figures 6 and 7 shows how the characteristics of both direct-driven and accumulator-driven systems vary for different type of forging operations. Such parameters should be considered in ordering new presses and in making economical use of existing equipment.

Mechanical Presses

The drive of most mechanical presses in use today (crank and eccentric) is based on the slider-crank mechanism which translates rotary into reciprocating motion, as in an internal combustion engine.[14, 15, 16] An electric motor and "V" belts drive a flywheel that is connected through a clutch and brake system to a pinion gear. The pinion gear is connected to the crank or eccentric shaft thus transmitting the available torque at the clutch and the available flywheel energy to the press slide. The flywheel stores energy that is used only during a small portion of the crank revolution, namely during deformation.

Kinematics of the Slider-Crank Mechanism

The slider-crank mechanism is presented schematically in Figure 8. The following valid relationships can be derived from the geometry illustrated in Figure 8.

The distance (w) of the slide from the bottom dead center (BDC) position is given by

$$w = r \left(1 - \cos\alpha + \frac{r}{2\ell}\sin^2\alpha\right) \quad , \qquad (8)$$

where, as seen in Figure 8a,

r = radius of the crank or half of the total stroke, $2r = S$

ℓ = length of the pitman arm

α = crank angle before BDC.

Since the ratio (r/ℓ) is usually small, Equation (8) can be approximated by

$$w = r\,(1 - \cos\alpha) = \frac{S}{2}(1 - \cos\alpha) \quad , \qquad (9)$$

where $S = 2r$ is the stroke of the press.

Equation (9) gives the location of the slide at a crank angle (α) before the BDC. This curve is plotted in Figure 8b along with the slide velocity (V) which is given by

$$V = r\,\frac{\pi n}{30}\left(\sin\alpha + \frac{r}{2\ell}\sin 2\alpha\right) \quad , \qquad (10)$$

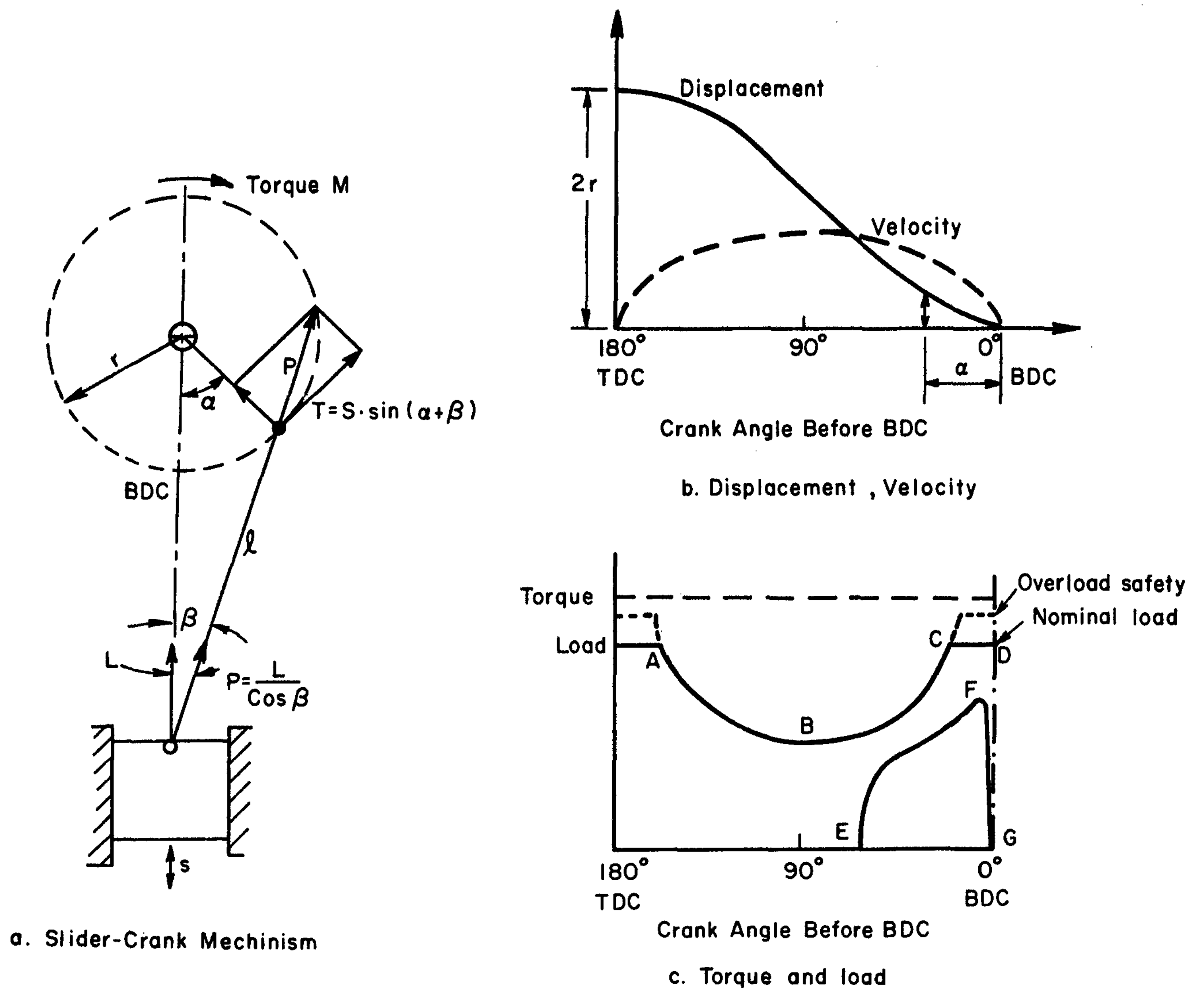


FIGURE 8. LOAD, DISPLACEMENT, VELOCITY, AND TORQUE IN A SIMPLE SLIDER-CRANK MECHANISM

and after approximation

$$V = r \frac{\pi n}{30} \sin \alpha = \frac{S\pi n}{60} \sin \alpha \quad , \tag{11}$$

where

n = number of strokes per minute.

The slide velocity (V) with respect to slide location (w) before BDC is given by

$$V = w \frac{\pi n}{30} \sqrt{\frac{S}{w} - 1} = 0.105 \, wn \sqrt{\frac{S}{w} - 1} \quad . \tag{12}$$

Thus, Equations (9) and (11) give the slide position and the slide velocity at an angle (α) before BDC. Equation (12) gives the slide velocity for a given position (w) before BDC if the number of strokes per minute (n) and the press stroke (S) are known.

Load and Energy Characteristics

The following relation exists between the torque (M) of the crankshaft and the available load at the slide; Figures 8a and 8c.[18, 19]

$$L = \frac{M}{r} \frac{\cos \beta}{\sin (\alpha + \beta)} \quad . \tag{13}$$

The torque (M) has a constant value for which the drive mechanism (i.e., crankshaft, pinion gear, clutch, brake, etc.) is designed.

As seen in Figure 8a, (α) and (β) represent the crank and pitman-arm angles before BDC, respectively. β is small for all practical purposes (maximum β = 6 degrees for $\ell/r = 10$); consequently Equation (13) can be approximated as

$$L = \frac{M}{r \sin \alpha} = \frac{2M}{S \sin \alpha} \quad . \tag{14}$$

Equation (14) gives the variation of the available slide load (L) with respect to the crank angle (α) before BDC, as seen in Figure 8c. From Equation (14) it is seen that as the slide approaches the BDC, i.e., as Angle (α) approaches zero, the available load (L) may become infinitely large without exceeding the constant clutch torque (M), i.e., without causing the friction clutch to slip.

From the observations made so far, the following conclusions are drawn:[14, 15]

(1) The crank and the eccentric presses are displacement-restricted machines. The slide velocity (V) and the available slide load (L) vary according with the position of the slide before BDC. Most manufacturers in the United States and in the United Kingdom rate their presses by specifying the nominal load at 1/2 inch before

BDC. For different applications, the nominal load may be specified at different positions before BDC according to the standards established by the American Joint Industry Conference.[14]

(2) If the load required by the forming process is smaller than the load available at the press (i.e., if the curve EFG in Figure 8c remains below the curve BCD), the process can be carried out provided the flywheel can supply the necessary energy per stroke.

(3) For small angles (α) before BDC, within the CD portion of the curve BCD in Figure 8c, the slide load (L) can become larger than the nominal press load if no overload safety (hydraulic or mechanical) is available on the press. In this case, the press stalls, the flywheel stops, and the entire flywheel energy is transformed into deflection energy by straining the press frame, the pitman arm, and the drive mechanism. The press can be freed in most cases only by burning out the tooling.

If the load curve EFG exceeds the press load BCD, Figure 8c, before the Point C is reached, then the friction clutch slides, the press slide stops, but the flywheel continues to turn. In this case the press can be freed by increasing the clutch pressure and by reversing the flywheel rotation if the slide has stopped before BDC.

The energy needed for the forming process during each stroke is supplied by the flywheel which slows down to a permissible percentage, usually 10 to 20 percent, of its idle speed. The total energy stored in a flywheel is:

$$E_{FT} = \frac{I\omega^2}{2} = \frac{I}{2}\left(\frac{\pi n}{30}\right)^2 , \tag{15}$$

where

I = moment of inertia of the flywheel

ω = angular velocity in radians per second

n = rotational speed of the flywheel.

The total energy (E_S) used during one stroke is:

$$E_S = \frac{1}{2}\, I \left(\omega_o^{\,2} - \omega_1^{\,2}\right) = \frac{I}{2}\left(\frac{\pi}{30}\right)^2 \left(n_o^{\,2} - n_1^{\,2}\right) , \tag{16}$$

where

ω_o = initial angular velocity

ω_1 = angular velocity after the work is done

n_o = initial flywheel speed

n_1 = flywheel speed after the work is done.

Note that the total energy (E_S) also includes the friction and elastic deflection losses. The electric motor must bring the flywheel from its slowed down speed (n_1) to its idle speed (n_o) before the next stroke for forging starts. The time available between two strokes depends upon the mode of operation, namely continuous or intermittent. In a continuously operating mechanical press, less time is available to bring the flywheel to its idle speed, consequently a larger horsepower motor is necessary.

Very often the allowable slowdown of the flywheel is given in percentage of the nominal speed. For instance, if 13 percent slowdown is permissible, then

$$\frac{n_o - n_1}{n_o} = \frac{13}{100} \text{ or } n_1 = 0.87\, n_o \quad . \tag{17}$$

The percentage energy supplied by the flywheel is obtained by using Equations (15) and (16) to give:

$$\frac{E_S}{E_{FT}} = \frac{n_o^2 - n_1^2}{n_o^2} = 1 - (0.87)^2 = 0.75 \quad . \tag{18}$$

Equations (17) and (18) illustrate that for a 13 percent slowdown of the flywheel, 25 percent of the flywheel energy will be used during one stroke.

Time-Dependent Characteristics

The number of strokes per minute (n) was discussed as part of the energy considerations.

For a given idle-flywheel speed, the contact time under pressure (t_p) and the velocity under pressure (V_p) depend mainly upon the dimensions of the slide-crank mechanism and upon the total stiffness (C) of the press. The effect of press stiffness upon contact time under pressure (t_p) is illustrated in Figure 9.[8] As the load

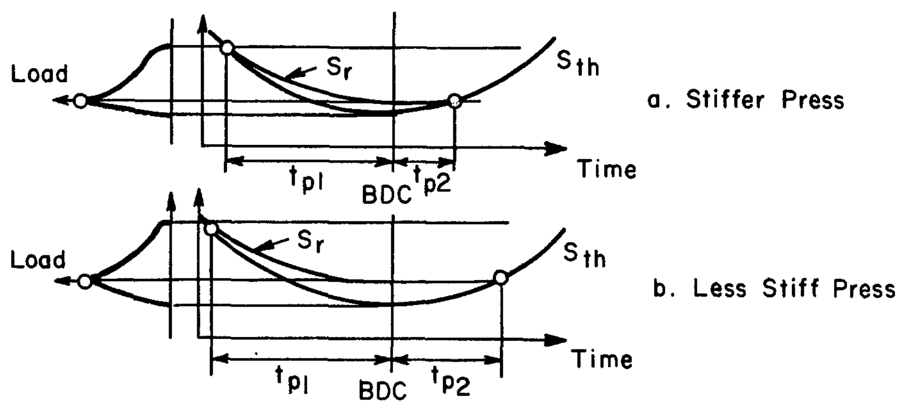


FIGURE 9. EFFECT OF PRESS STIFFNESS UPON CONTACT TIME UNDER PRESSURE[8]

(S_{th} = theoretical displacement-time curve, S_r = real displacement-time curve under load.)

builds up, the press deflects elastically. A stiffer press (larger C) requires less time (t_{p1}) for pressure build-up and also less time (t_{p2}) for pressure release, as seen in Figure 9a. Consequently, the total contact time under pressure ($t_p = t_{p1} + t_{p2}$) is less for a stiffer press.

Characteristics for Accuracy

The working accuracy of a forging press is substantially characterized by two features: the tilting angle of the ram under off-center loading and the total deflection under load or stiffness of the press. The tilting of the ram produces skewed surfaces and an offset on the forging; the stiffness influences the thickness tolerance.[20]

Under off-center loading conditions two- or four-point presses perform better than single-point presses since the tilting of the ram and the reaction forces into gib-ways are minimized.[21] A new type of mechanical press called the "wedge-type press" has been claimed to reduce tilting under off-center loading in both directions (front to back and left to right) and to offer increased overall stiffness. The design principle of the wedge-type press is shown in Figure 10. In this press, the load acting upon the ram is supported by the wedge which is driven by a two-point crank mechanism.

Assuming the total deflection under load for a one-point eccentric press to be 100 percent, the following distribution of the total deflections was obtained after measurements under nominal load on the same-capacity forging presses:[20]

	Eccentric Press One Point	Eccentric Press Two Point	Wedge Press
Slide + Pitman Arm	30%	21%	21% (includes wedge)
Frame	33%	31%	29%
Drive Shaft + Bearings	37%	33%	10%
Total Deflection	100%	85%	60%

It is interesting to note that a large percentage of the total deflection is in the drive mechanism, i.e., slide, pitman arm, drive shaft and bearings.

For the same presses discussed above, Figure 11 illustrates the table-load diagrams which show, in the percentage of the nominal load, the amount and location of off-center load that causes tilting of the ram. The wedge-type press presents advantages, especially in front-to-back off-center loading. In this respect it performs like a four-point press.

Screw Presses

The screw press, along with hammers and mechanical presses, is the most widely used type of equipment for die forging in European forging industry. In the United States only a small number of companies are using screw presses for forging or coining operations. Since screw presses offer distinct advantages in certain types of forming operations, it can be expected that more forgers will be interested in this type of equipment as information becomes available and more experience is accumulated.

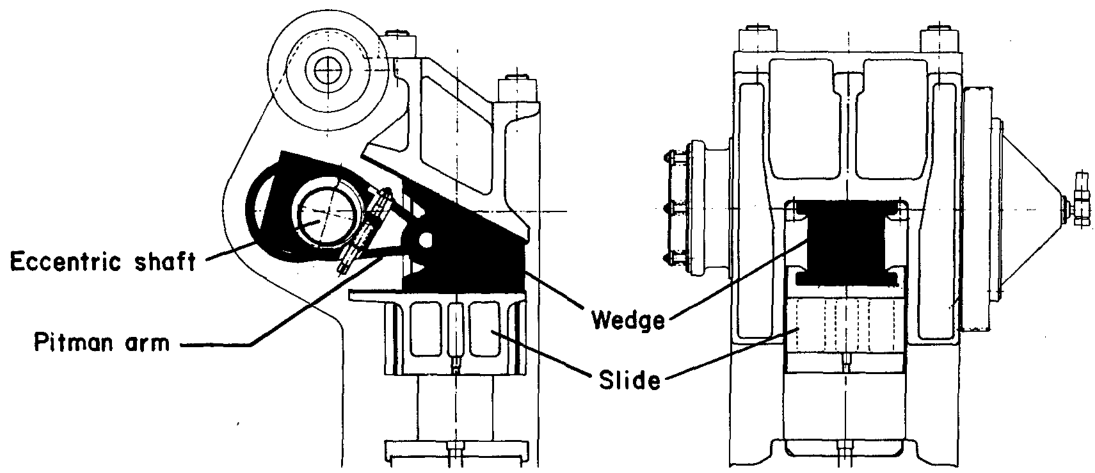


FIGURE 10. PRINCIPLE OF THE WEDGE-TYPE MECHANICAL PRESS[20]

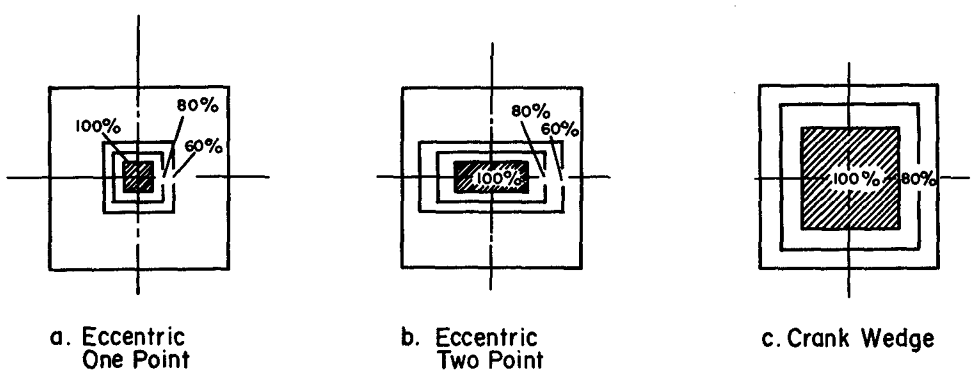


FIGURE 11. TABLE-LOAD DIAGRAMS FOR THREE TYPES OF FORGING PRESSES OF THE SAME NOMINAL LOAD ILLUSTRATING LOCATION AND MAGNITUDE OF OFF-CENTER LOADING[20]

The screw press uses either a friction or a hydraulic drive to accelerate the flywheel and the screw assembly moves the ram. Figure 12 shows three designs of friction-screw presses.(15) In the type of press shown in Figure 12a, the friction wheels are mounted on a horizontal shaft and are rotated continuously through a "V" belt drive from an electric motor. For a downstroke, one of the friction wheels is pressed against the flywheel by a servo-motor.(13,22) The flywheel is connected to the screw either positively or by a friction slip clutch. The friction wheel accelerates the flywheel and the connected screw. Through this rotary motion the screw and the attached press slide move downward while the kinetic energy of the flywheel continues to increase. This is similar to the dropping ram of a hammer. When the slide hits the workpiece the deformation starts. The load necessary for forging builds up and is transmitted through the slide, the screw, and the bed to the press frame. When the entire energy in the flywheel is used in deforming the workpiece and elastically deflecting the press, the flywheel, the screw, and the slide stop. At this moment, or slightly earlier, the servo-motor activates the horizontal shaft and presses the up-stroke friction wheel against the flywheel. Thus, the flywheel and the screw are accelerated in the reverse direction and the slide is lifted to its top position.

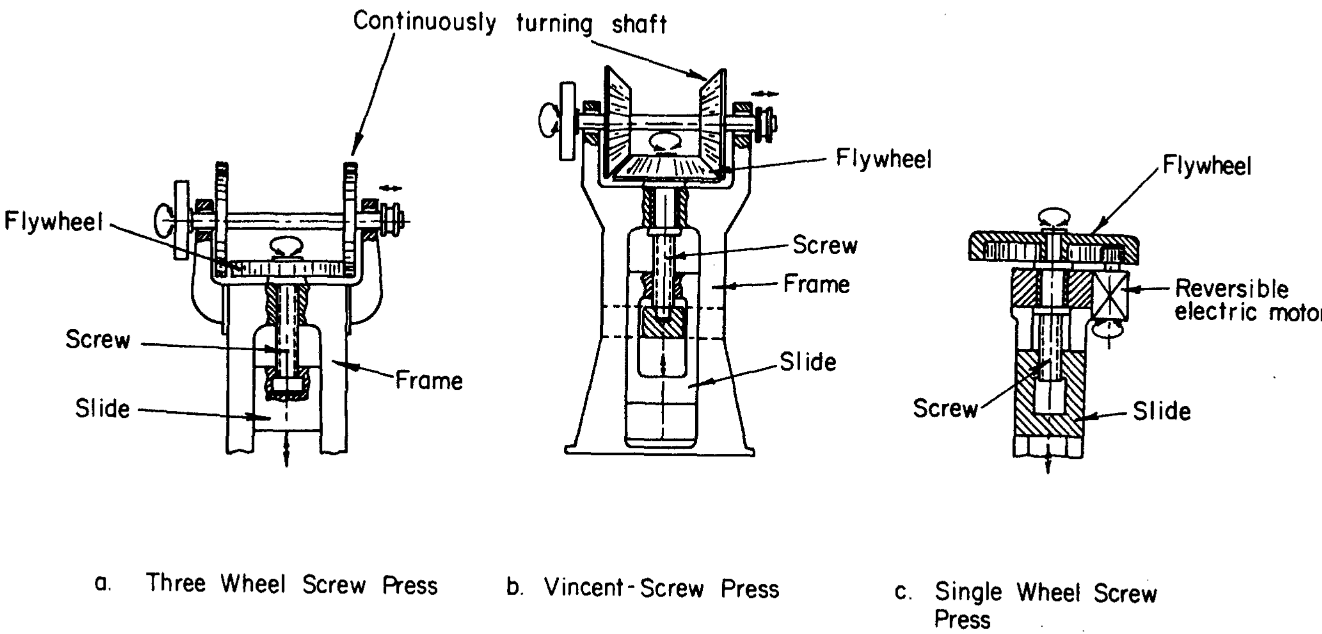


FIGURE 12. DIFFERENT TYPES OF FRICTION-SCREW PRESSES

The type of press shown in Figure 12b is called a "Vincent-screw press"; it operates essentially in the manner described above. The difference is that the screw is threaded at a yoke connected to the press bed. Consequently, during a downstroke, while the screw is turning, the ram remains stationary and the lower bed moves upward.

In the press shown in Figure 12c there are no friction wheels. The flywheel is accelerated by an electric motor through a friction drive. To reverse the direction of rotation of the flywheel, the electric motor is reversed after each downstroke and upstroke. In this design, the screw is threaded into the ram and does not move vertically while the ram moves up and down.

Load and Energy

In screw presses the forging load is transmitted through the slide, screw, and bed to the press frame. The available load at a given stroke position is supplied by the stored energy in the flywheel. During downstroke the flywheel and the screw are accelerated by a friction drive (Figure 12) or by a hydraulic drive (in new designs and larger capacity presses). At the end of the downstroke, i.e., after the forging blow, the flywheel comes to a standstill and starts its reversed rotation. During the standstill, i.e., at BDC the flywheel no longer contains any energy. Thus, the total flywheel energy (E_{FT}) has been transformed into:[6, 19]

(1) Available energy for deformation (E_M) to carry out the forging process

(2) Friction energy (E_f) to overcome frictional resistance in the screw and in the gibs

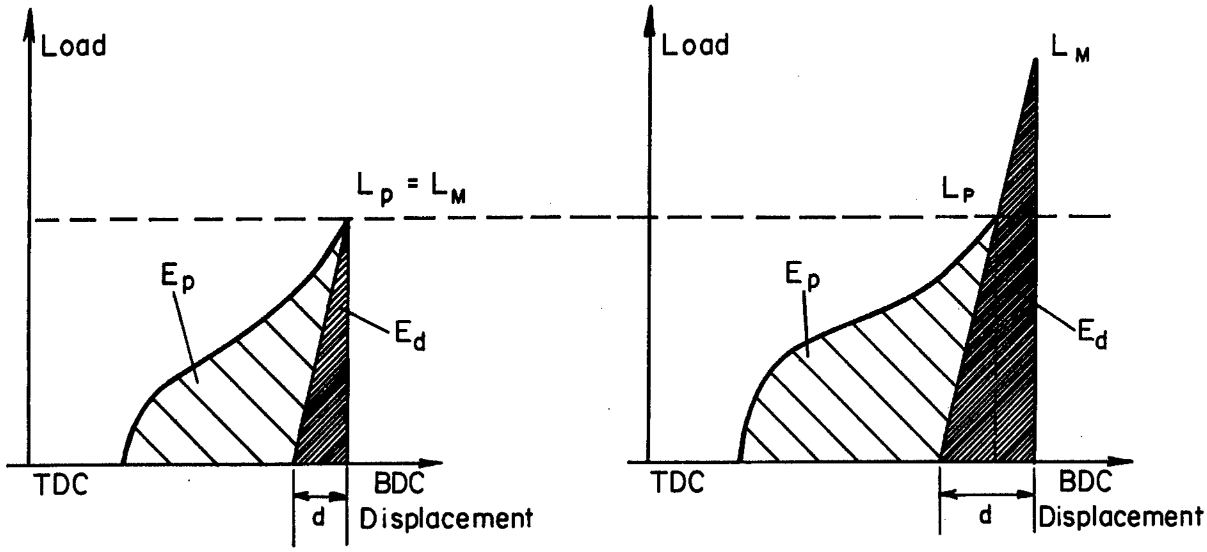
(3) Deflection energy (E_d) to elastically deflect various parts of the press.

At the end of a downstroke the deflection energy (E_d) is stored in the machine and can be released only during the upward stroke.

The load-versus-displacement diagrams of a forging operation are illustrated in Figure 13. The flywheel in Figure 13a is accelerated to such a velocity that at the end of downstroke the deformation is carried out and no unnecessary energy is left in the flywheel. This is done by using an energy metering device which controls the flywheel velocity. The flywheel in Figure 13b has excess energy at the end of downstroke. The excess energy caused additional unnecessary elastic straining of the press by being transformed into additional deflection energy.

From the above discussion it is seen that, in screw presses, the load and the energy are in direct relation with each other. For a given press (i.e., for the same friction losses, elastic deflection properties and available flywheel energy) the load available at the end of the stroke depends mainly upon the deformation energy required by the process (i.e., on the shape, temperature, and material of the workpiece). Thus, for a constant flywheel energy, low deformation energy (E_p) results in high end load (L_M), and high deformation energy (E_p) results in low end load (L_M). These relations are illustrated in the "load-energy diagram" of a screw press as shown in Figure 14.

The screw press can generally sustain maximum loads (L_{max}) up to 160 to 200 percent of its nominal load (L_M). In this sense, the nominal load of a screw press is set rather arbitrarily. The significant information about the press load is obtained from its load-energy diagram as seen in Figure 14. Many screw presses have a friction clutch built between the flywheel and the screw. When the ram load reaches the nominal load, this clutch starts slipping and uses up a part of the flywheel energy as friction heat energy (E_c) at the clutch. Consequently the maximum load at the end of downstroke is reduced from (L) to L_{max}), Figure 14.

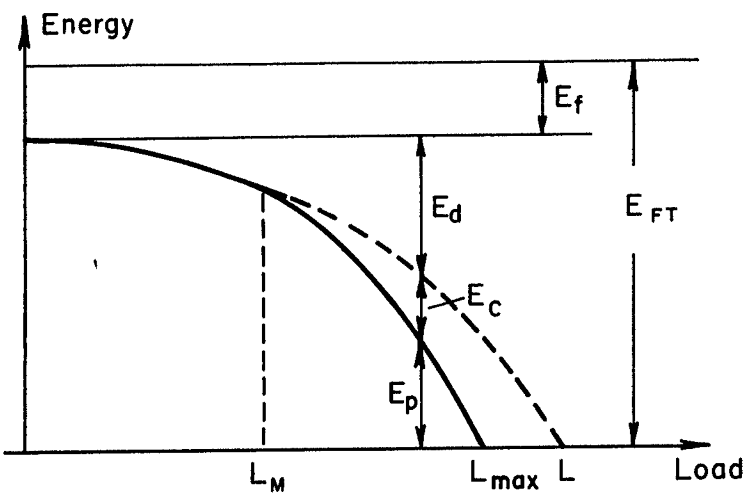


a. With Energy Metering

b. Without Energy Metering

E_p = energy required by process
L_p = load required by process
L_M = maximum machine load
E_d = elastic deflection energy
d = elastic deflection of the press.

FIGURE 13. LOAD AND ENERGIES IN DIE FORGING UNDER A SCREW PRESS



--- without friction clutch at flywheel
—— with slipping friction clutch at flywheel
E_{FT} = total flywheel energy
E_f = friction energy
E_d = deflection energy
E_P = energy required by process
E_c = energy lost in slipping clutch
L_M = nominal machine load
L_{max} = maximum load.

FIGURE 14. ENERGY-LOAD CURVE OF A SCREW PRESS

The energy-versus-load curve has a parabolic shape as seen in Figure 14. The energy decreases with increasing load. This is due to the fact that the deflection energy (E_d) is given by a second order equation

$$E_d = \frac{1}{2} dL = \frac{L^2}{2C} \quad , \tag{19}$$

where

d = elastic deflection of the press

L = load

C = total stiffness of the press.

A screw press can be designed such that the press can sustain hard blows (e.g., die-to-die blows without any workpiece) for maximum energy of the flywheel. In this case no friction clutch between flywheel and screw is used. The design of the press is dictated by its specific use. It is important to note that a screw press can be designed and used for forging operations where large deformation energies are required or for coining operations where small energies but high loads are required. Another interesting feature of screw presses is that they can not be loaded beyond the calculated overload limit of the press.

Time-Dependent Characteristics

For a screw press the number of strokes per minute (n) is a dependent characistic. Since modern screw presses are equipped with energy metering devices, the number of strokes per minute depends upon the energy required by the process. In general, however, the production rate of screw presses compares with that of mechanical presses.

The velocity under pressure (V_p) is generally higher than in mechanical presses but lower than in hammers. This is because the slide velocity of a mechanical press slows down towards the BDC and the velocity of the slide in a screw press accelerates until deformation starts and the load builds up. This fact is more pronounced in forging thin parts such as air-foils or in coining and sizing operations.

The contact time under pressure (t_p) is related directly to the ram velocity and to the stiffness of the press. In this respect, the screw press ranks between the hammer and the mechanical press. The contact times (t_p) for screw presses are 20 to 30 times longer than those for hammers.[23] A similar comparison with mechanical presses cannot be made without specifying the thickness of the forged part. In forging turbine blades, i.e., for small displacement but large load requirements, the contact times for screw presses have been estimated to be 1/4 to 1/10 of that for mechanical presses.[24]

Characteristic Data for Accuracy

In general, the considerations discussed for mechanical presses are also valid for screw presses.

The stiffness (C) of a screw press, in addition to influencing the thickness tolerances of a forging, also greatly affects the energy and load characteristics of the machine as described above.

In screw presses, in addition to static or quasistatic deflections, the dynamic behavior of the slide is also of importance. In this respect, the screw press behaves dynamically similar to drop hammers.[25]

Hammers

The hammer is the most economical type of equipment for generating load and energy necessary to carry out a forging process provided the material being forged can support high deformation velocities (160 to 240 in./sec).[26] Therefore, it is the most commonly used hot forging equipment, especially in the forging of steel. The hammer is an energy-restricted machine, therefore the capacity of a hammer must be given in energy units, i.e., kgm or ft-lb, but not in lb only. The hammer can be used for repeated blows on the same workpiece and cannot be overloaded.

There are various types of hammers. In a simple gravity drop hammer the upper ram is positively connected to a board (board drop hammer), a belt (belt drop hammer), or a chain (chain drop hammer). The upper ram is lifted to a certain height and then dropped upon the workpiece placed on the anvil. The force necessary to insure a quick lift-up of the ram can be equal to 3 to 5 times the ram weight.[4] During a downstroke, the ram accelerates by gravity and builds up the blow energy.

In an air-lift gravity drop hammer the ram is connected to a piston which is lifted by air pressure. The downstroke is, in principle, the same as that of in a simple gravity drop hammer.

Power drop hammers are driven by steam, air, or oil pressure. In downstroking, the ram is accelerated, in addition to gravity, by the pressure medium used. On the upstroke the ram is lifted by pressure through a cylinder-piston mechanism.

Counterblow hammers are widely used in Europe while their use in the United States is limited to a relatively small number of companies. In this type of hammer, the anvil and ram are accelerated toward each other. In most cases only one, the upper ram for instance, is power driven while the lower ram or anvil is either mechanically or hydraulically coupled with the upper ram. In counterblow hammers the vibration of the impact is reduced and very little energy is lost as vibration in the foundation and in the environment. The anvil is much smaller than that of drop hammers. The counterblow hammers are built for larger capacities up to 125,000 to 150,000 kgm and are used mostly in forging parts that do not have to be held in the dies while the forging blow strikes. A horizontal variation of the counterblow hammer, called an Impacter, also is used in the United States.

Load and Energy

In a gravity drop hammer the total energy at the ram is given by

$$E_T = \frac{1}{2} m_1 v_1^2 = \frac{1}{2} \frac{G_1}{g} V_1^2 = G_1 \cdot H \quad , \tag{20}$$

where

m_1 = the mass of the dropping ram

V_1 = velocity of the ram at the start of deformation

G_1 = weight of the ram

g = acceleration of gravity

H = height of the ram drop.

In a power drop hammer the total energy at the ram is given by[25]

$$E_T = \frac{1}{2} m_1 V_1^2 = (G_1 + p \cdot A) \cdot H \quad , \tag{21}$$

where, in addition to the symbols used in Equation (20),

p = air, steam, or oil pressure acting upon ram cylinder in downstroke

A = surface area of the ram cylinder.

Equation (20) indicates that in a gravity drop hammer, the total blow energy is equal to the kinetic energy of the ram and is generated solely through the free-fall velocity.

Equation (21) indicates that in a power drop hammer the total blow energy is generated by the free fall of the ram and by the pressure acting on the ram cylinder.

During hammer forging the total blow energy (E_T) is transformed into:

(1) Useful deformation energy for carrying out the process (E_P)

(2) Energy lost in elastic deflection and vibration of the ram

(3) Energy lost in elastic deflections and vibrations of the anvil and the foundation.

The ratio of the useful deformation energy (E_P) to the total blow energy (E_T) is called blow efficiency

$$\eta = \frac{E_P}{E_T} \quad . \tag{22}$$

The blow efficiency has a value of 0.8 to 0.9 for soft blows (in free-form forging) and 0.3 to 0.6 for hard blows (closed-die forging). The magnitude of the blow efficiency (η) depends upon the ratio of the anvil weight to the ram weight (10 to 25) and upon the kinematics of the blow, i.e., the instantaneous velocities of the ram and anvil after the blow.

In determining the overall efficiency of a hammer, in addition to blow efficiency, the efficiency of the driving system (electric motor, compressor, etc.) must also be considered.

In counterblow hammers, where both rams have the same weight, the total energy per blow is given by:

$$E_T = 2\left(\frac{m_1 V_1^2}{2}\right) = \frac{m_1 V_t^2}{4} = \frac{G_1 V_t^2}{4} \quad , \qquad (23)$$

where

m_1 = mass of one ram

V_1 = velocity of one ram

V_t = actual velocity of blow of the two rams

= $2V_1$

G_1 = weight of one ram.

The blow efficiency for counterblow hammers is in the same range as that for drop hammers having an anvil-to-ram weight ratio of 20 to 25.[26]

The forging loads developed under hammers are considerable. Since the hammer is an energy-restricted machine, the maximum load developed depends upon the characteristics of the specific forging process. If the energy supplied by the hammer exceeds the energy required by the process, the excess energy is transmitted to the ram, anvil, and foundation and is lost in the form of elastic deflections, vibrations, and noise. In gravity drop hammers there is no positive connection between the hammer frame and the ram, consequently the frame is subjected only to loads due to off-center loading and deflection of the ram within the guides.

Time-Dependent Characteristic Data

In a hammer, the number of strokes per minute (n) is particularly important when a workpiece is forged under repeated blows. The time that elapses between two consecutive blows greatly influences the heat transfer between the workpiece and the lower die and thus determines the magnitude of temperature drop in the workpiece. The number of strokes per minute is mainly determined by the drop height in gravity drop hammers, and by both the drop height and the pressure acting on the ram cylinder in power drop hammers.

The velocity under pressure (V_p) is determined mainly by the impact velocity of the ram (12 to 20 ft/sec in gravity drop hammers, 18 to 25 ft/sec in power drop hammers, and 16 to 25 ft/sec in counterblow hammers). The velocity of the ram, at impact and during deformation, is an important variable because it greatly influences the flow stress of the forged material. This is due to the fact that the flow stress of metals are strain-rate or deformation-rate dependent at hot-forging temperatures.

The contact time under pressure (t_p) ranges from 1 to 10 milliseconds. These values are lower than for any other commonly used forging equipment except for HERF machines. The contact time (t_p) might depend upon the lifting mechanism and the control of the ram. In this case it would be useful to have experimental values on the time response of the control system.

Characteristic Data for Accuracy

For the unloaded machine, the same general considerations are valid as those for all other types of forging equipment. These considerations were discussed under the general review of equipment characteristics.

In determining accuracy under load, however, it is important to know the extent that the ram might be tilted by an off-center blow. In this respect, the hammers having large ram velocities behave quite different from presses.[24] In hard blows, with short contact times under pressure (t_p), the ram is tilted only by external forces within the clearances of the guides. Consequently, in such blows the ram tilting depends upon the geometrical inaccuracies in the ram and anvil and upon the inertia of the ram. In soft blows, with longer contact times, the tilting behavior of the ram depends also upon the stiffness of the guides and of the frame.

DISCUSSION

In the first part of this study, forging process variables related to equipment are reviewed and, using the classification suggested by Kienzle[5], the most important machine characteristics are discussed. In the second part, each type of forging machine is discussed within the scope of suggested equipment characteristics. This discussion explains the differences between various types of forging equipment.

The improvement of the forging process is closely related to the understanding and efficient use of equipment capabilities. Increased knowledge on forging equipment would be useful for both supplier and user and would contribute to the improvement of the state of the art in forging and in forging-equipment design. Although significant research and development appears to have been done in other countries such as the Soviet Union, Germany, and England, very little technically useful information is available in the U. S. technical literature on forging equipment and its applications.

A similar trend is observed in the development and practical application of sophisticated and automated forging equipment. Many U. S. companies are purchasing very advanced new equipment from European suppliers. Screw presses, for instance, are built solely by European manufacturers and are considered to be best suitable for precision forging of air-foils and gears. Although these presses are considered standard equipment in the European forging industry, only during the past few years, they have been introduced by some companies in the United States. With few exceptions, major design innovations in manufacture of equipment for hot forging appears to come from European sources, although U. S. manufacturers offer quite advanced automatic-feeding and -handling equipment. Completely automatic hot-forging stations are, however, largely supplied by German and Swiss press manufacturers. The following quotation from Steel magazine[27] illustrates this point: "Europe Leads. Though it is difficult to say where automated hot forging started (Chevrolet was using an automated Ajax machine to make rocker arms in 1932), there is little doubt that the recent success stories have come mostly from Europe and Japan."

The present state of the art in forging-equipment use and manufacture indicates that (1) equipment characteristics and capabilities must be well understood and applied in designing forging operations as well as in purchasing equipment, and (2) more research and development work must be carried out concerning the design and automation of forging equipment. In the next decade, automation, N/C and computer applications will be increasingly introduced into forging technology and European competition in this field will be quite significant.

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